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David P. (Powell) LeMaster, B.E.S.

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AIRPORT PERFORMANCE ESTIMATION FOR POWERED LIFT AIRCRAFT

THESIS

AFIT/GAE/AA/78D-15 DAVID P. LEMASTER

Preface

My objective in this study was directed primarily toward the takeoff and landing analysis of the Advanced Medium STOL Transport (AMST) aircraft, the YC-14 and YC-15, designed by the Boeing Company and the McDonnell-Douglas Corporation, respectively. The data presented, however, does not represent either of the AMST candidates. The data is normalized in a purely arbitrary manner where the normalizing function changes from configuration to configuration and also parameter to parameter. To further confuse the matter, the configuration designator also changes from parameter to parameter. The purpose is so that prediction method may be compared to actual aircraft performance but the actual aircraft may not be compared at this time because of the competition sensitive status of the AMST program.

My appreciation is extended to Dr. C. Philip Poirier for his diligent efforts in providing the necessary computer programming and for his valuable counsel. I would also like to express my appreciation to my wife, Diana, for her encouragement and assistance.

DAVID P. LEMASTER

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List of Symbols

Symbol	Definition
a	Acceleration
C_D	Longitudinal force coefficient
C_J	Gross thrust coefficient
C_L	Normal force coefficient
D	Aerodynamic drag
DR	Engine ram drag
E	Total energy
F	Net accelerating force
F_G	Engine gross thrust
FGTD	Gross thrust at touchdown
g	Gravitational constant
h_{obs}	Obstacle height
I_{yy}	Pitch moment of inertia
L	Aerodynamic lift
M	Aircraft pitching moment
N_z	Normal load factor
q	Dynamic pressure
R	Ground resistance
RSOBS	Rate of sink at the obstacle
S	Aircraft wing reference area
T	Takeoff segment time
Δt_{ROT}	Incremental time for the rotation segment
V	Aircraft true airspeed
V_{APP}	Landing approach velocity
V_F	Velocity to initiate flap deflection
V_g	Aircraft ground velocity

Symbol	Definition
V_{LO}	Liftoff velocity
V_{OBS}	Obstacle clearance velocity
V_{TD}	Landing touchdown velocity
V_W	Wind velocity
W	Aircraft gross weight
x	Horizontal distance
α	Angle of attack
α_{LO}	Liftoff angle of attack
α_{TAXI}	Taxi angle of attack
α_{TD}	Landing touchdown angle of attack
γ	Flight path angle
δ_F	Flap deflection angle
η	Reverse thrust turning angle
ϕ	Runway slope

Abstract

A numerical technique based on known methods was developed to predict the takeoff and landing performance characteristics of powered lift aircraft. Two-degree-of-freedom equations of motion treating the aircraft as a point mass are integrated using numerical techniques based on Euler's method of forward integration. The analysis includes the calculation of all engines operating takeoff distance, critical field length, landing distance and climb capability. Predictions were made for aircraft with externally blown flaps and upper surface blown flaps and compared with the performance quoted by the respective airframe manufacturer. Good correlation was achieved.

AIRPORT PERFORMANCE ESTIMATION

FOR

POWERED LIFT AIRCRAFT

I. Introduction

Problem

Estimation of an aircraft's airport performance; i.e., takeoff and landing characteristics, is a difficult problem because it involves not only the aircraft's physical and dynamic characteristics but also the atmospheric and runway conditions in which the aircraft must operate as well as the variations caused by the different piloting techniques. Compounding the problem is the fact that when the exact force equations are written, the equations of motion are not integrable in closed form. Powered lift aircraft further aggravate the problem with the interdependence of the propulsive and aerodynamic forces.

Background

Operational considerations for both civil and military transport aircraft have caused increased emphasis on the ability to operate from shorter airfields than the current generation of jet transports. Although no specific definition exists for Short Takeoff and Landing (STOL) performance, the U. S. Air Force requirement (Ref 5) is stated as the capability to operate into and out of a 2,000 ft airfield which represents about a 50 percent improvement in takeoff and landing performance.

The runway required for a given aircraft gross weight can be reduced by: (1) increasing the aircraft thrust; (2) increasing the aircraft wing area; or, (3) reducing the takeoff and landing speeds through improved high lift devices. This is, however, not easily accomplished because simply increasing the thrust and/or wing area results in too great a penalty in the aircraft's cruise performance and the available mechanical flap systems are just not capable of producing the maximum lift coefficient required. Engine augmented high lift systems appear to be a possible solution. Several powered lift concepts have been built and tested with varying degrees of success. Two of the more promising concepts, upper surface blown flaps (Ref 4) and externally blown flaps (Ref 1), have recently (1973-77) been built and flown in the USAF's Advanced Medium STOL Transport (AMST) prototype program.

Many solutions, such as Houghton (Ref 2: 184-190), are published where simplifying assumptions are used to reduce the equations of motion into a closed integrable form. These solutions, however, dilute the computational precision such that it is not possible to differentiate, as is required in a technical evaluation, among the capabilities of the competing bidder's configurations. Other solutions, such as Jansen (Ref 3), using numerical methods for integration have been developed for conventional aircraft. Unfortunately, these solutions are not applicable to powered lift aircraft because they cannot accomodate the engine power contribution to the lift force. In addition, powered lift aircraft are particularly sensitive to design parameters such as flap deflection schedule, pitch rate, minimum control speed, etc. Consequently, many parameters which were either neglected or linearized for conventional aircraft must now be modeled for powered lift aircraft.

Objective

The objective of this study was to develop an analytical technique, using numerical methods to integrate the equations of motion, for the parametric analysis of the takeoff and landing characteristics of aircraft using an engine powered high lift system.

Approach

Aircraft performance analysis in the vicinity of the airport is defined to include: (1) all engines operating takeoff distance; (2) critical field length; and, (3) landing distance as illustrated in Figures 1, 2, and 3, respectively. Climb capability in the takeoff and go-around configurations is also included.

In Chapter II the equations of motion for each segment are developed with particular attention given to the assumptions necessary to obtain a practical solution. The overriding assumption for all the segments is that the forces acting on the aircraft are constant over each integration step and thereby allows the equations to be numerically integrated.

The analytical development begins very simply with Newton's second law of motion and uses Euler's method of forward integration to solve the equations of motion. The aircraft is treated as a point mass with two degrees of freedom using a coordinate system aligned with the wind axis. The analytical treatment is general in nature allowing the analysis to include variations in the aircraft design parameters, ambient conditions, runway conditions and pilot reactions. Independent variables included in the analytical model are: gross weight, wing area, number of engines, gross thrust and ram drag, aerodynamic data, flap deflection and deflection rate, fuselage ground clearance angle, taxi angle of attack, thrust reverser effectiveness, spoiler effectiveness, landing gear

limit rate of sink, ambient temperature, pressure altitude, wind velocity, rolling and braking coefficients of friction, runway slope, and pilot reaction times for engine failure recognition, brake application, spoiler deployment, and thrust reverser deployment.

Chapter III contains the results of a comparison for the AMST configurations between the performance quoted by the respective airframe manufacturer and the performance predicted using the method discussed in Chapter II. Sensitivity of the predictions to the various parameters are also discussed. Conclusions regarding the developed method are presented in Chapter IV.

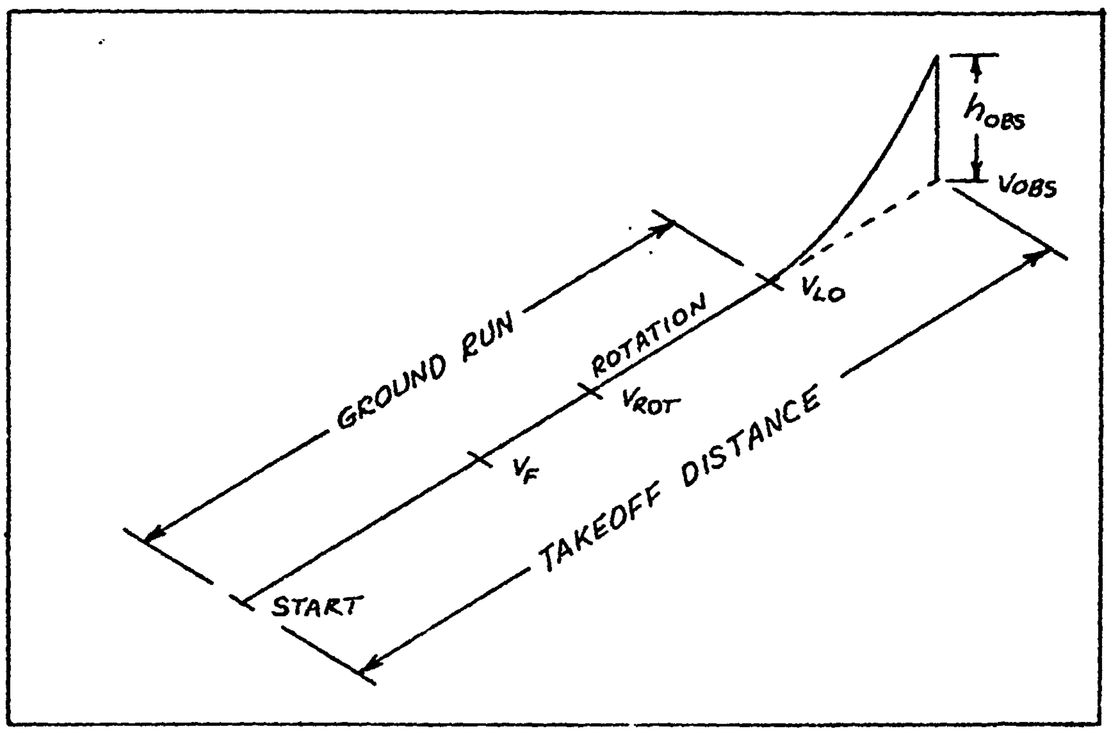

Figure 1. Takeoff Distance Schematic

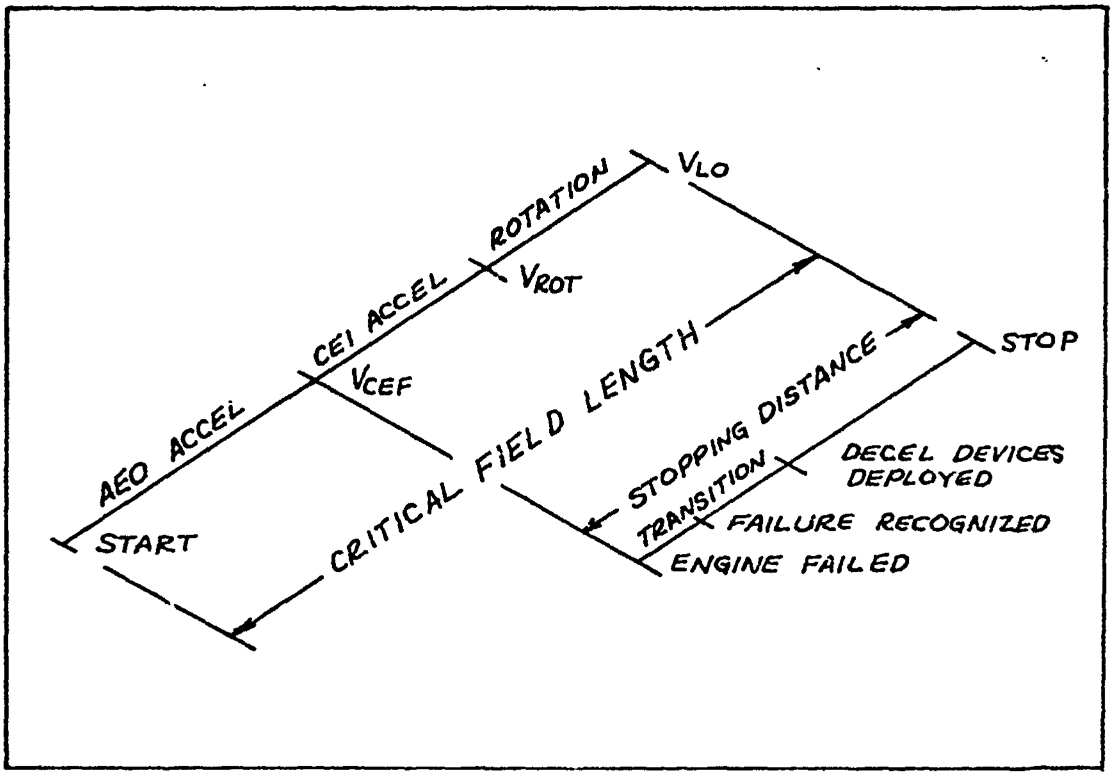

Figure 2. Critical Field Length Schematic

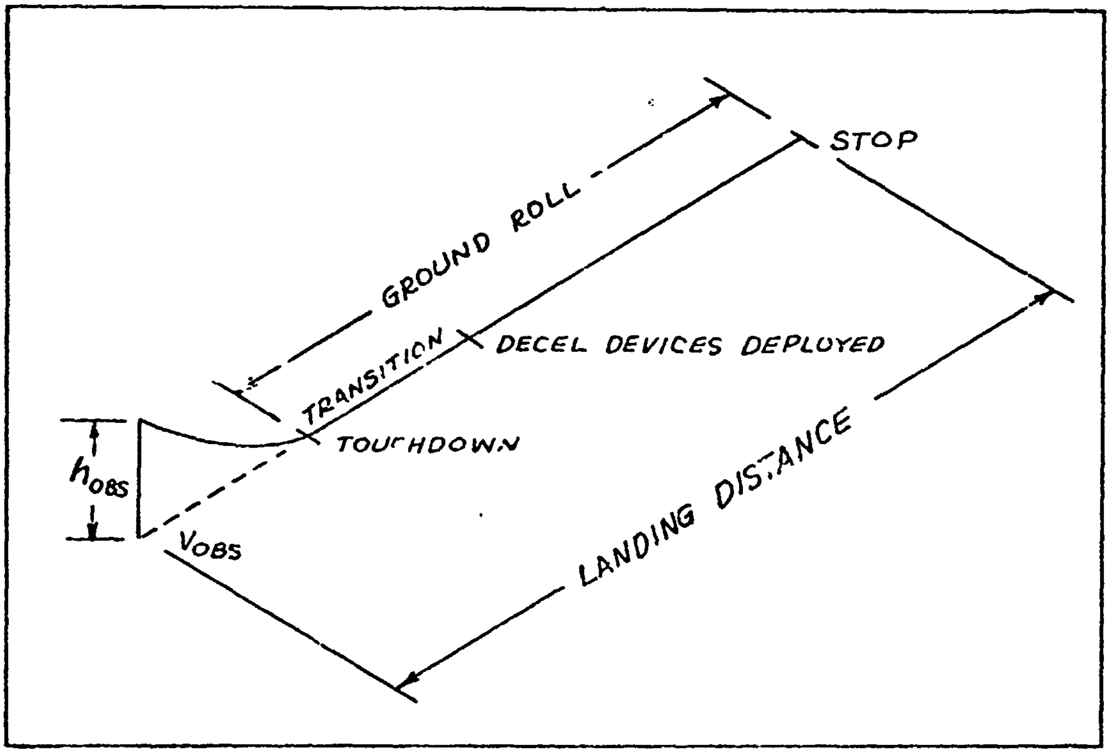

Figure 3. Landing Distance Schematic

II. Development of Analytical Solution

Since the purpose of this method is to predict the takeoff and landing distances only and not to analyze any aircraft stability or control characteristics, the first simplifying assumption is to treat the problem as a two degree of freedom point mass and therefore eliminate the need to provide input data for aircraft inertias and the control power about the aircraft axes. The second simplifying assumption is to maintain a constant gross weight throughout the takeoff or landing. The most significant assumption required is to assume the forces acting on the aircraft are constant over each integration step. The analytical treatment is then divided into three major sections: (1) takeoff distance; (2) critical field length; and (3) landing distance.

Takeoff Distance

Takeoff distance as illustrated in Fig. 1 is commonly defined as the horizontal distance to accelerate on the ground to liftoff and climb out to a specified height. For most military applications the obstacle height is 50 ft while for civil applications the obstacle height is 35 ft. The takeoff distance is divided into two segments: ground run and climb out. While the ground run is defined as the distance from brake release to liftoff, it is convenient to separate it into a constant attitude acceleration segment and a rotation segment where the angle of attack varies from the taxi attitude to the lift off angle of attack.

Aircraft using engine powered flap systems such as externally blown flaps or upper surface blown flaps can be sensitive to the flap position during the ground roll because of the turning of the thrust vector by the flap system. As a result, an additional velocity cue, V_F is defined

during the takeoff ground run as the velocity to initiate the extension of the flaps to the takeoff position.

Ground Run. Beginning with Newton's second law of motion, $F = ma$, it can easily be shown that the distance traveled along the ground is given by:

$$x = \int \frac{W V_g}{F g} \, dV_g \tag{1}$$

where

x = ground distance

V_g = aircraft ground velocity

F = net accelerating force

g = gravitational constant

The influence of wind on the takeoff distance can easily be accounted for by letting $V_g = V - V_w$ where V is the aircraft true airspeed relative to the wind and V_w is the wind velocity relative to the ground. Substituting into eq (1) yields:

$$x = \int \frac{W V}{F g} \, dV - \int \frac{W V_w}{F g} \, dV \tag{2}$$

The wind velocity is in general unsteady because of the randomly occurring gusts in nature. However, over short periods of time the average wind is steady. Therefore, for the takeoff and landing analyses, it is assumed that the wind velocity is constant and the second integral of eq (2) is simply a constant, V_w, times the integral of $\frac{dV}{a}$ which, when integrated, is the time required to accelerate between the specified end velocities. The ground distance equation then becomes:

$$X = \int_{V_2}^{V_1} \frac{WV}{Fg}\, dV - (T)(V_w) \tag{3}$$

where T = Time to accelerate from V_1 to V_2

V_w = Steady wind velocity (+ = headwind)

In order to evaluate this integral, the instantaneous forces acting on the aircraft must be determined. Because the aircraft is treated as a point mass, the total resistance due to ground friction can be expressed as one force. The individual forces acting on the aircraft are depicted in Fig 4 where:

F_G = Engine gross thrust

D = Aircraft aerodynamic drag

DR = Engine ram drag

R = Ground resistance = $\mu(W-L)$

L = Aircraft lift

W = Aircraft gross weight

ϕ = Runway slope

μ = Coefficient of friction

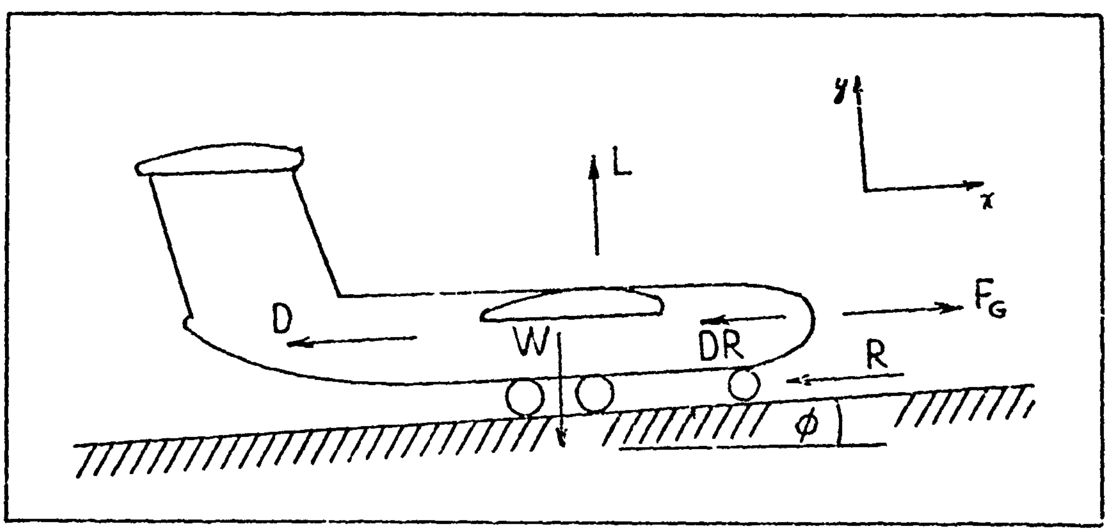

Figure 4. Forces Acting During Ground Run

These forces are defined in the terms commonly used for conventional aircraft; however, the interaction of the aerodynamic and propulsion systems makes it impractical to determine explicitly the values of gross thrust components, lift, and drag. Force data for powered lift aircraft can be obtained in the wind tunnel using a powered model. The longitudinal and normal forces that are measured include the propulsion effects and are both a function of engine power setting. The same force vectors as shown in Fig 4 are applicable to powered lift aircraft except that F_G is no longer needed and is deleted. In this case, L is redefined as the net normal force and D is redefined as the net longitudinal force. These forces are also nondimensionalized by dividing by the dynamic pressure and wing reference area. Longitudinal force (drag - thrust) coefficient, C_D, now has both positive and negative values where a negative drag coefficient means that the engine thrust component is greater than the aerodynamic drag. The parameter used to define the engine power setting is thrust coefficient, C_J, which is defined as the engine gross thrust divided by dynamic pressure and wing reference area. The aerodynamic coefficients for powered lift aircraft are presented in the general form $C_L = f(C_J, \alpha, \delta_F)$ and $C_D = g(C_J, \alpha, \delta F)$ as illustrated in Figures 5 and 6 where δF is the flap deflection angle and α is the aircraft angle of attack. Note that thrust coefficient is defined with velocity in the denominator and is, therefore, undefined when the aircraft velocity is zero. In order to prevent this, the thrust coefficient is inverted and now goes to zero at zero velocity. The force coefficients are also "inverted" by dividing by the thrust coefficient which causes the nonlinearity as the velocity approaches zero with the regular coefficients to become relatively linear functions

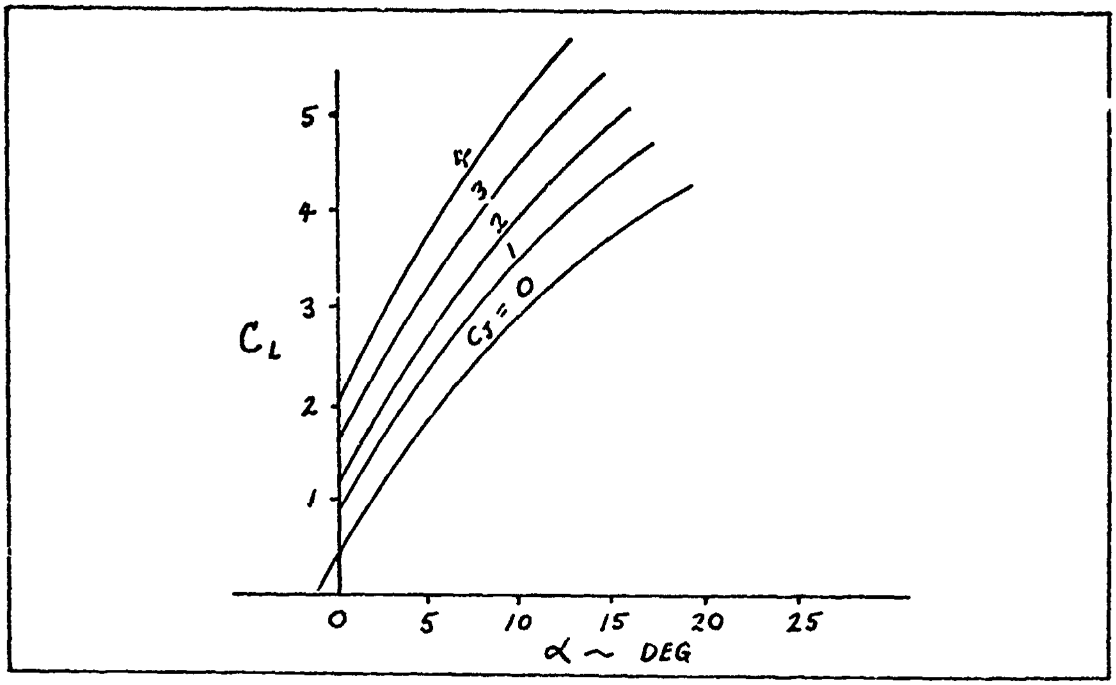

Figure 5. Normal Force (Lift) Coefficient Data

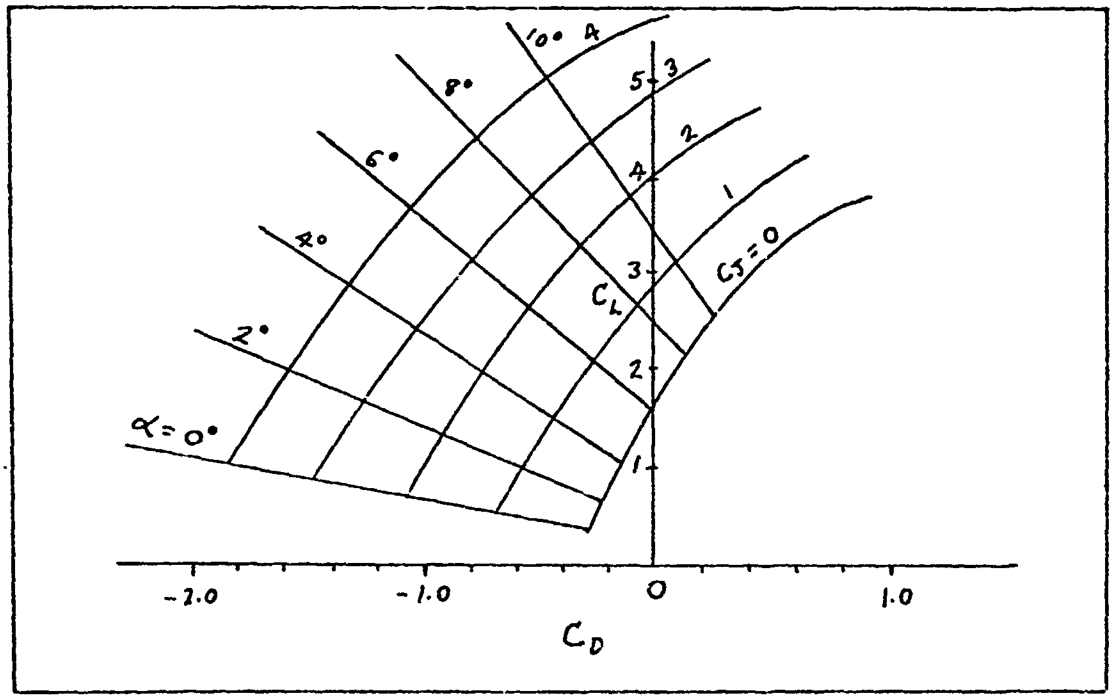

Figure 6. Longitudinal Force (Drag - Thrust) Coefficient Data

in the inverted form. For digital processing, the data is, therefore, handled as $CL/_{CJ} = f\left(\frac{1}{CJ}, \alpha, \delta_F\right)$ and $\frac{CD}{CJ} = g\left(\frac{1}{CJ}, \alpha, \delta F\right)$.

The net accelerating force acting on the aircraft during the ground run can be expressed:

$$F = - C_D qS - DR - \mu(W\cos\emptyset - C_L qS) - W\sin\emptyset \tag{4}$$

where

F = Net accelerating force

C_D = Net longitudinal force coefficient

C_L = Net formal force coefficient

DR = Engine ram drag

q = Dynamic pressure

S = Aircraft wing reference area

W = Aircraft gross weight

μ = Coefficient of friction

$\emptyset$ = Runway slope

Substituting eq (4) into eq (3) and writing in its form for numerical integration gives:

$$\Delta X = \frac{WV}{g}\left[\frac{1}{-C_D\, q\, S - DR - \mu\,(W\cos\emptyset - C_L qS) - W\sin\emptyset}\right]\Delta V - (T)(V_w) \tag{5}$$

The numerical integration is performed using Euler's method of forward integration. Since this technique assumes that the forces are constant over the integration interval, the step size, ΔV, must be selected carefully to maintain the integrity of this assumption.

Rotation. In this phase the aircraft is rotated from its taxi attitude to the pitch attitude at liftoff which requires the addition of a new variable, rotation rate, due to the finite time of rotation. In order to maintain precision in the computation, minimize the input data required for the analysis and model the dynmaic response of the

aircraft which has in fact a large pitch moment of inertia and still retain the point mass assumption, it is assumed that the net pitching moment acting on the aircraft is applied by the pilot's control input where the pitching moments due to angular displacement and angular velocity are neglected as higher order terms since the total angular displacement and maximum rotation rates are small. The pitching moment, M, applied by the pilot is assumed constant through the first half of the rotation segment followed by a reversal in pilot control input during the second half of rotation in order to arrest the rotation rate by the time liftoff is achieved. Therefore, during rotation

$$I_{yy}\,\ddot{\alpha} = M \tag{6}$$

where

I_{yy} = Aircraft pitch moment of inertia

$\ddot{\alpha}$ = Aircraft pitch acceleration

M = Pilot applied pitching moment

Integrating eq (6) twice and applying boundary conditions of $\dot{\alpha} = 0$ and $\alpha = \alpha_{taxi}$ at $t = 0$ results in

$$\alpha = \frac{M}{2\,I_{yy}}\,t^2 + \alpha_{taxi} \tag{7}$$

where

α = Instantaneous angle of attack

α_{taxi} = Taxi angle of attack

t = Time

Evaluating at $t = \frac{\Delta t_{ROT}}{2}$ where $\alpha = \frac{\alpha_{LO}}{2}$, then:

$$\frac{M}{2\,I_{yy}} = \frac{2\,(\alpha_{LO} - 3\,\alpha_{taxi})}{(\Delta t_{ROT})^2} \tag{8}$$

where

Δt_{ROT} = Time for rotation segment

α_{LO} = Liftoff angle of attack

Substituting eq (8) into eq) gives

$$\alpha = kt^2 + \alpha_{taxi} \tag{9}$$

for $\alpha_{taxi} \leq \alpha \leq \frac{\alpha_{LO}}{2}$

and $$\alpha = -k(t - t_{ROT})^2 + {}_{LO} \tag{10}$$

for $\frac{\alpha_{LO}}{2} \leq \alpha \leq \alpha_{LO}$

where $$k = \frac{2(\alpha_{LO} - 3\,\alpha_{taxi})}{(\Delta t_{ROT})^2}$$

The initial value for Δt_{ROT} is estimated by assuming the time histogram during rotation is a quadratic function of velocity, $\Delta t = a + b\,V^2$, where the constants a and b are evaluated using the time increments computed at the rotation and liftoff velocities. This time estimate is used to compute the initial rotation rate which is then modified using an iterative procedure using the last computed value for Δt_{ROT} until the liftoff angle of attack and liftoff velocity are achieved simultaneously.

Climb Out. The horizontal distance to climb and accelerate from the liftoff point to the specified obstacle height and velocity is written:

$$x_{air} = \int_{E_1}^{E_2} \frac{dx}{dt}\frac{dt}{dE}\,dE \tag{11}$$

Assuming that the vertical velocity is a small compared to the horizontal velocity:

$$E_1 = \frac{W\,V_{LO}^{\;2}}{2g} \tag{12}$$

$$E_2 = W\left[(V_{OBS}\cos\gamma_2)^2 + h_{OBS}\right] \tag{13}$$

where E_1 = Aircraft energy at liftoff

E_2 = Aircraft energy at the obstacle

V_{LO} = Velocity at liftoff

V_{OBS} = Velocity at obstacle

γ_2 = Flight path angle at obstacle

h_{OBS} = Height of obstacle

and
$$dE = V \cos\gamma \left(\frac{W}{g}\right) \left(a_t \cos\gamma - a_n \sin\gamma\right) \tag{14}$$

where a_t = Acceleration tangent to the flight path

a_n - Acceleration normal to the flight path

$$\frac{dx}{dt} = V \cos\gamma \tag{15}$$

Substituting eq (14) and eq (15) into eq (11)

$$x_{air} = \frac{g}{W} \int_{E_1}^{E_2} \frac{dE}{(a_t \cos\gamma - a_n \sin\gamma)} \tag{16}$$

Assume the average acceleration $\bar{a} = \frac{a_1 + a_2}{2}$ and an average flight path angle $\bar{\gamma} = \frac{\gamma_1 + \gamma_2}{2}$, eq (16) is integrated to obtain

$$x_{air} = \frac{V_{OBS}^2 \cos^2\gamma_2 - V_{LO}^2 + 2g\, H_{OBS}}{(2) \quad (\bar{a}\cos\bar{\gamma} - N_z g \sin\bar{\gamma})} \tag{17}$$

where N_z = load factor normal to the flight path

Critical Field Length

Critical field length as illustrated in Fig 2 is defined as the length of runway required to accelerate with all engines operating to the critical engine failure speed, experience a failure of the most critical engine, and either continue to accelerate with the engine inoperative to liftoff or decelerate to a complete stop in the remaining runway. The critical engine failure velocity is defined as the velocity at which the acceleration to liftoff distance is equal to the stopping

distance and, therefore, becomes the pilot's takeoff decision speed; i.e., if a failure occurs before the critical engine failure speed, the aircraft is stopped; if the failure occurs after the critical engine failure speed, the aircraft must continue to accelerate to liftoff. The critical field length analysis is divided into four segments: (1) all engines operating (AEO) acceleration to the critical engine failure speed; (2) continued acceleration with the critical engine inoperative (CEI); (3) rotation; and (4) stopping distance.

Acceleration Distance. The distances for the three acceleration segments of the critical field length are computed using the same technique described above for the takeoff ground run. Since an actual engine failure can be anything from an explosive loss of the engine to ruptured fuel line, the worst case is assumed and the failed engine is modeled by setting the thrust instantaneously to zero at the engine failure velocity. The change in flap deflection angle, if applicable, is also initiated at the engine failure velocity.

Stopping Distance. The stopping distance includes a segment where the aircraft transitions from the accelerating configuration to the decelerating configuration and a constant configuration maximum deceleration segment. The transition segment begins at the engine failure velocity and is complete when all of the deceleration devices are deployed. During this segment time delays are included for the pilot to recognize the engine failure, chop the throttle, apply the brakes, initiate spoiler deployment, and initiate thrust reverser deployment. The brakes are assumed to be applied as a step function, but the spoiler and thrust reverser deployment are modeled with linear functions. The engine thrust decay after the throttle chop and the reverse thrust

build-up are also modeled with linear functions. The net longitudinal force defined by eq (4) is modified to include the force components due to reverse thrust and becomes:

$$F = -C_D qS - DR - (W - C_L qS + F_G \sin\eta) - F_G \cos\eta \tag{18}$$

where η = Reverse thrust turning angle

Flight Path Capability. The climb capability of an aircraft with an engine inoperative in the takeoff or the landing go-around configuration is frequently the limiting parameter on the allowable gross weight or the allowable takeoff or landing speeds. This is particularly true for aircraft using powered lift flaps because the engine exhaust flowing over the flaps delays the flow separation and allows the use of larger flap deflections than the conventional aircraft. The steady state climb angle is given by:

$$\gamma = \sin^{-1}\left(\frac{C_D qS - DR}{W}\right) \tag{19}$$

Landing Distance

Landing distance as illustrated in Fig 3 is defined as the total horizontal distance from a specified obstacle height to a complete stop. The landing distance is divided into two segments, air phase and ground roll.

Air Phase. The air phase is defined as the horizontal distance from the specified obstacle height to touchdown. For both military and civil applications, the obstacle height is 50 ft. Normally the flight path consists of a constant glide slope segment followed by a pilot initiated flare or round-out to reduce the rate of sink at touchdown. As a result, the distance traveled during the air phase is highly dependent on the piloting technique. For STOL aircraft, the landing

gear is stronger, allowing a larger touchdown rate of sink and the technique is to fly the constant glide slope into the ground with the only flare or reduction in rate of sink coming from increased lift due to the aircraft flying into the presence of the ground. Therefore, the air phase is modeled by writing the energy equation, eq (16), and integrating from E_2 to E_1 where E_2 is the aircraft energy at the obstacle and E_1 is the energy at touchdown yields

$$x_{air} = \frac{V_{OBS}^2 \cos^2 \gamma_2 - V_1^2 + 2gh_{OBS}}{(2)\ (\bar{a} \cos \gamma_{avg} - N_z g \sin \gamma_{avg})} \qquad (20)$$

where

x_{air} = Landing air distance

V_{TD} = Velocity at touchdown

V_{OBS} = Landing approach velocity

$\bar{a}$ = Average acceleration during air phase

γ_{avg} = Average flight path algne during air phase

N_z = Normal load factor during flare

The power setting and angle of attack required to fly the approach flight path is computed:

$$C_D = \frac{(RSOBS)\ (T)}{(V_{OBS})\ (q)S} \qquad (21)$$

$$CL = \frac{W \cos \gamma_{APP}}{q\ S} \qquad (22)$$

$$C_J = (CL,\ C_D,\ \delta_F) \qquad (23)$$

$$TD = (CL,\ CD,\ \delta_F) \qquad (24)$$

$$FGTD = (C_J)\ q\ S \qquad (25)$$

where

RSOBS = Rate of sink at the obstacle height

γ_{APP} = Approach flight path angle

FGTD = Gross thrust at touchdown

γ TD = Angle of attack at touchdown

Ground Roll. The landing stopping distance is calculated using the same technique used for the critical field length stopping segment except that the transition segment for landing also must model the aircraft rotating from the touchdown pitch attitude to the taxi attitude. In this case, a linear model is used with the rotation rate provided in the input data. Touchdown gross thrust and angle of attack are assumed to be equal to that required to fly the approach flight path.

III. Results and Discussion

The principal result of this study was the digital computer program, AIRPORT, written using the equations developed in Chapter II. A description of the program with functional definitions of the key subroutines is contained in Appendix A.

The program was used to predict the takeoff and landing characteristics of the Advanced Medium STOL Transport (AMST) aircraft, the YC-14 and YC-15. Due to the competitive nature of the AMST program, the data cannot be presented in absolute values. For correlation of the analytical method, the field length and gross weights are normalized using different factors for each parameter and powered lift configuration.

The all engines operating takeoff ground run data is presented in Fig. 7. The difference in the AIRPORT predicted ground run as compared to the distance predicted by the respective airframe contractors varied from 0.5 percent to 0.8 percent for one contractor and from 0.6 percent to 2.1 percent for the other. The overall average difference of 1.1 percent is considered excellent correlation.

Figure 8 shows the comparison of the total all engines operating takeoff distance. In this case, the difference with the contractor data varied from 3.2 to 12.5 percent for one contractor and from 14.0 to 20.0 percent for the other. The average variation for one contractor was 6.9 percent while the average for the other was 17.4 percent. The correlation is not good, per se, but it does show that the distance predicted by AIRPORT is reasonable. It also suggests that a disparity exists between the contractors' prediction methods. A possible contributing factor to the poor correlation is the assumption that the vertical velocity is small relative to the horizontal velocity.

The critical field length comparison is presented in Fig. 9. The difference for the critical field length varies for one contractor from 2.3 percent to 5.8 percent while the variation for the other contractor is from 0.5 to 4.6 percent. The average difference is 2.9 percent and is considered good correlation.

Figure 10 shows the comparison of the landing ground roll and Fig. 11 shows the total landing distance comparison. The difference for the ground roll for one contractor varied from 1.5 to 4.5 percent for an average difference of 2.9 percent, while the difference with the other contractor varied from 4.4 to 13.3 percent for an average difference of 7.9 percent. The overall average difference for the ground roll is 5.4 percent. The differences in total landing distance was approximately the same for both contractors where the variation ranged from 0.8 percent to 5.6 percent with the average difference of 2.9 percent. Overall correlation of the total landing distance and landing ground roll is good.

The sensitivity of critical field length to the various conditions and parameters is often ignored because it takes a unique happening for the takeoff to become critical--the failure must occur very close to the computed critical engine failure speed when the aircraft is operating at the maximum allowable gross weight for the runway. When it does, the results are startling. For example, for each second the pilot delays in brake application, the critical field length would only increase 30 feet for a nominal critical field of 2000 feet. The startling part is that once an aircraft is committed to a takeoff with a computed critical engine failure speed of 70 knots and then the pilot delays in the application of the brakes, the stopping distance increases at the rate of 120 feet per second of delay. The critical field length does not show a significant increase because the field length balances at a lower critical

engine failure velocity.

The quadratic model for takeoff rotation described in Chapter II was compared to a model where angle of attack changed linearly. The difference in the computed rotation distances was on the order of one foot for the all engines operating case and from one to three percent for the engine inoperative case. The change in critical field was about one percent. However, for the case where the aircraft is rotated too rapidly and reaches the liftoff angle of attack before the liftoff velocity is reached, the rotation distance increased 13 percent for reaching the liftoff angle two knots early.

Other parameters that can be analyzed using program AIRPORT that can have a significant effect on takeoff and landing performance are ambient temperature, pressure altitude, runway surface, brake effectiveness and thrust reverser effectiveness.

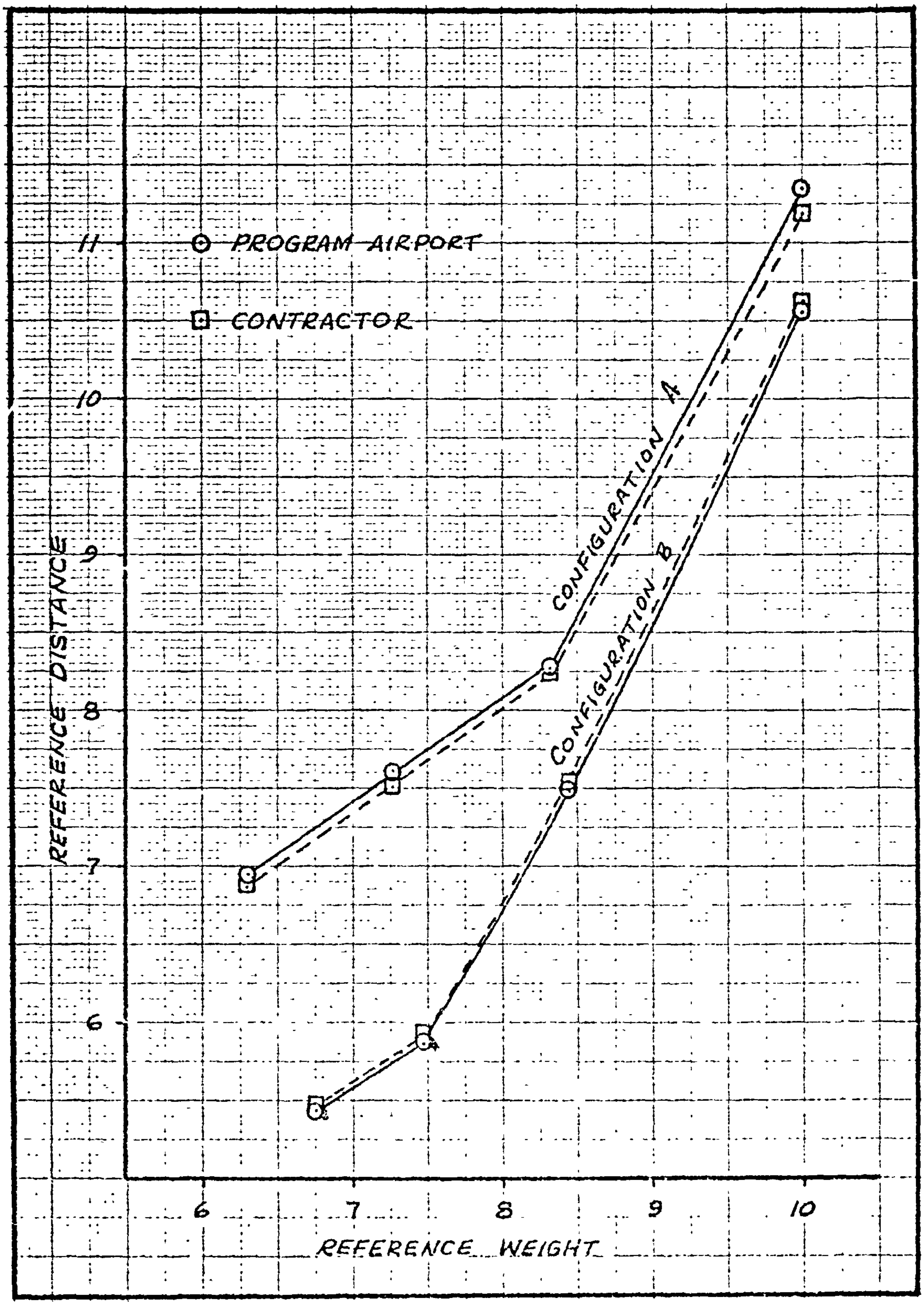

Figure 7. Takeoff Ground Run Comparison

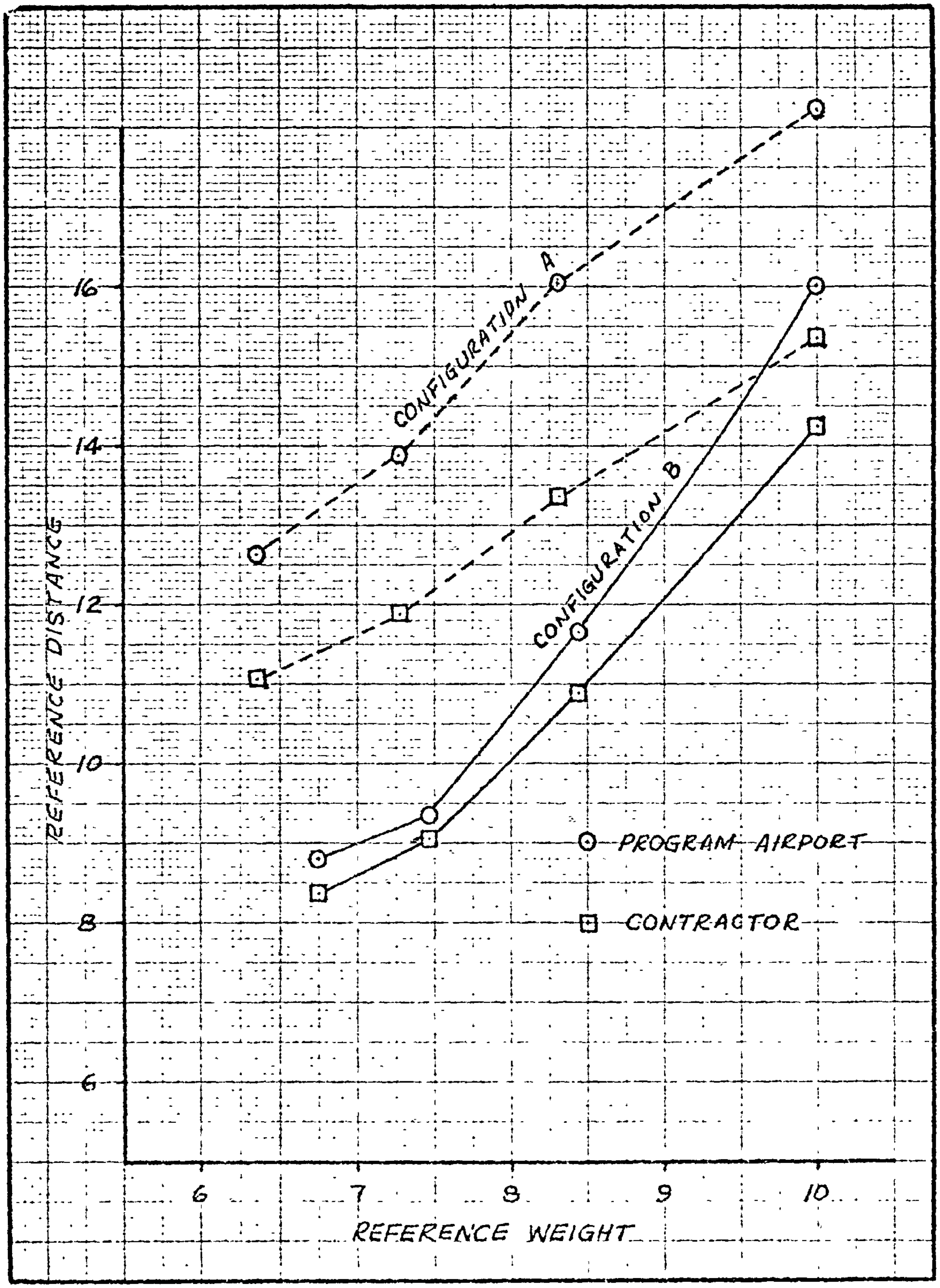

Figure 8. Takeoff Distance Comparison

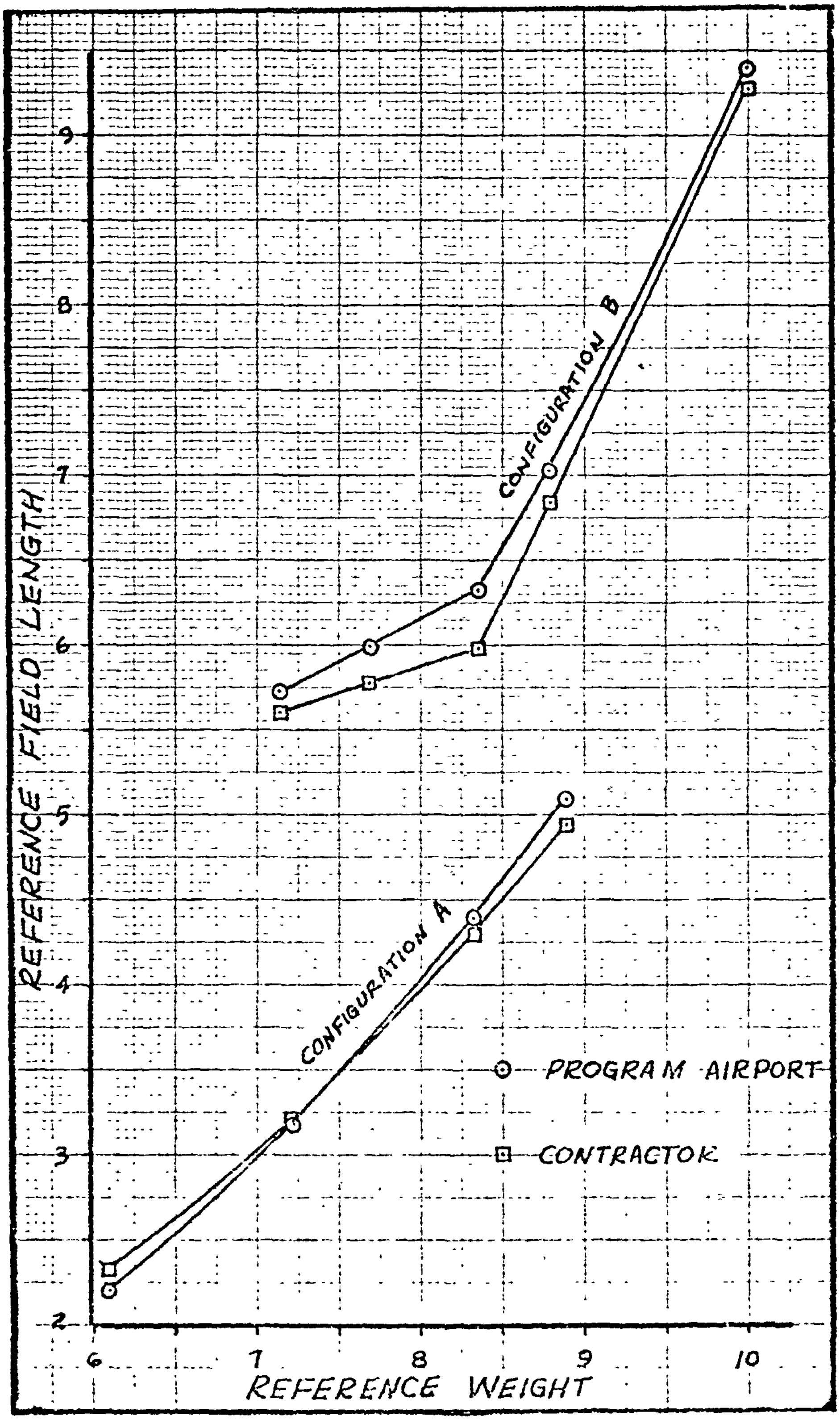

Figure 9. Critical Field Length Comparison

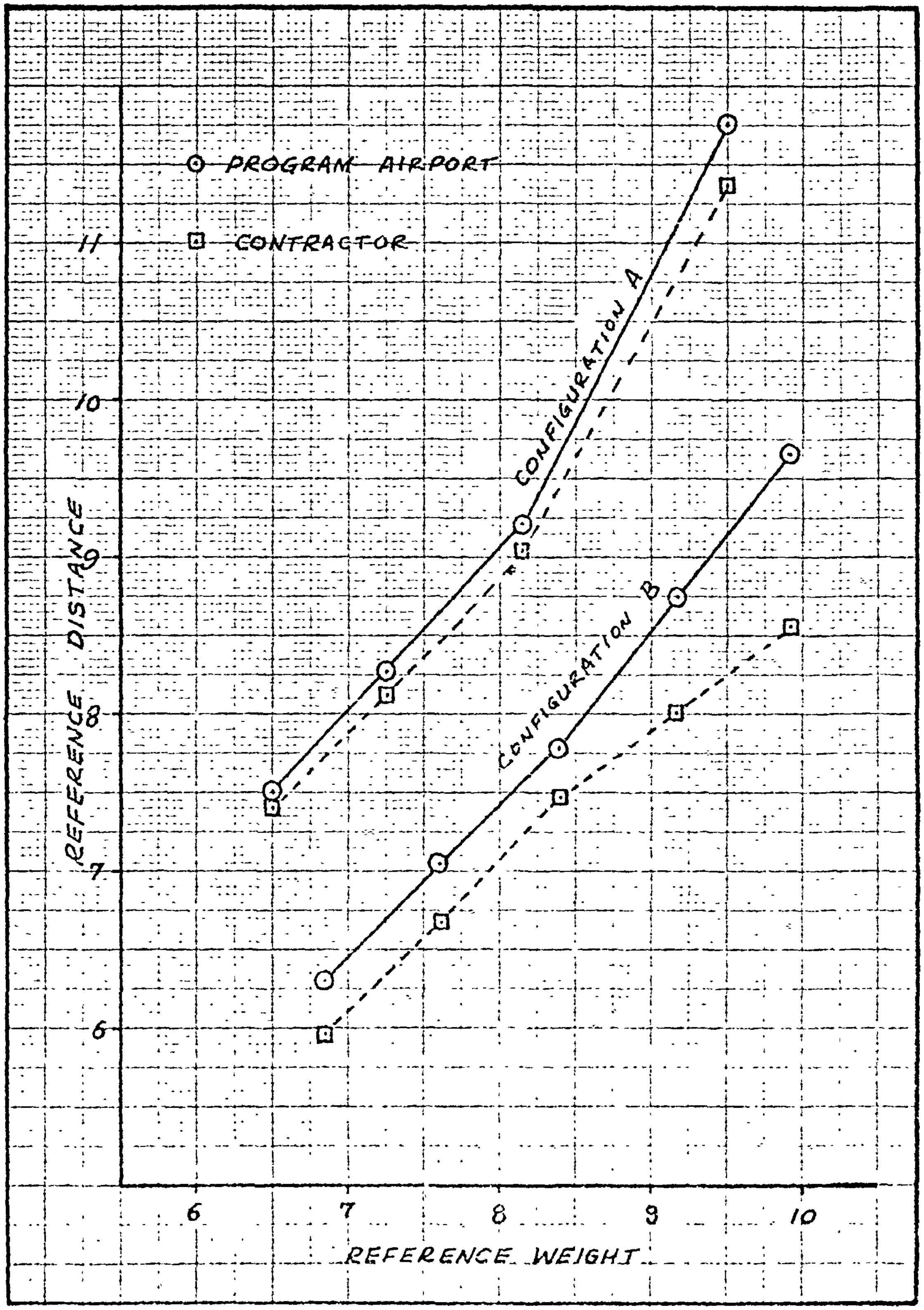

Figure 10. Landing Ground Roll Comparison

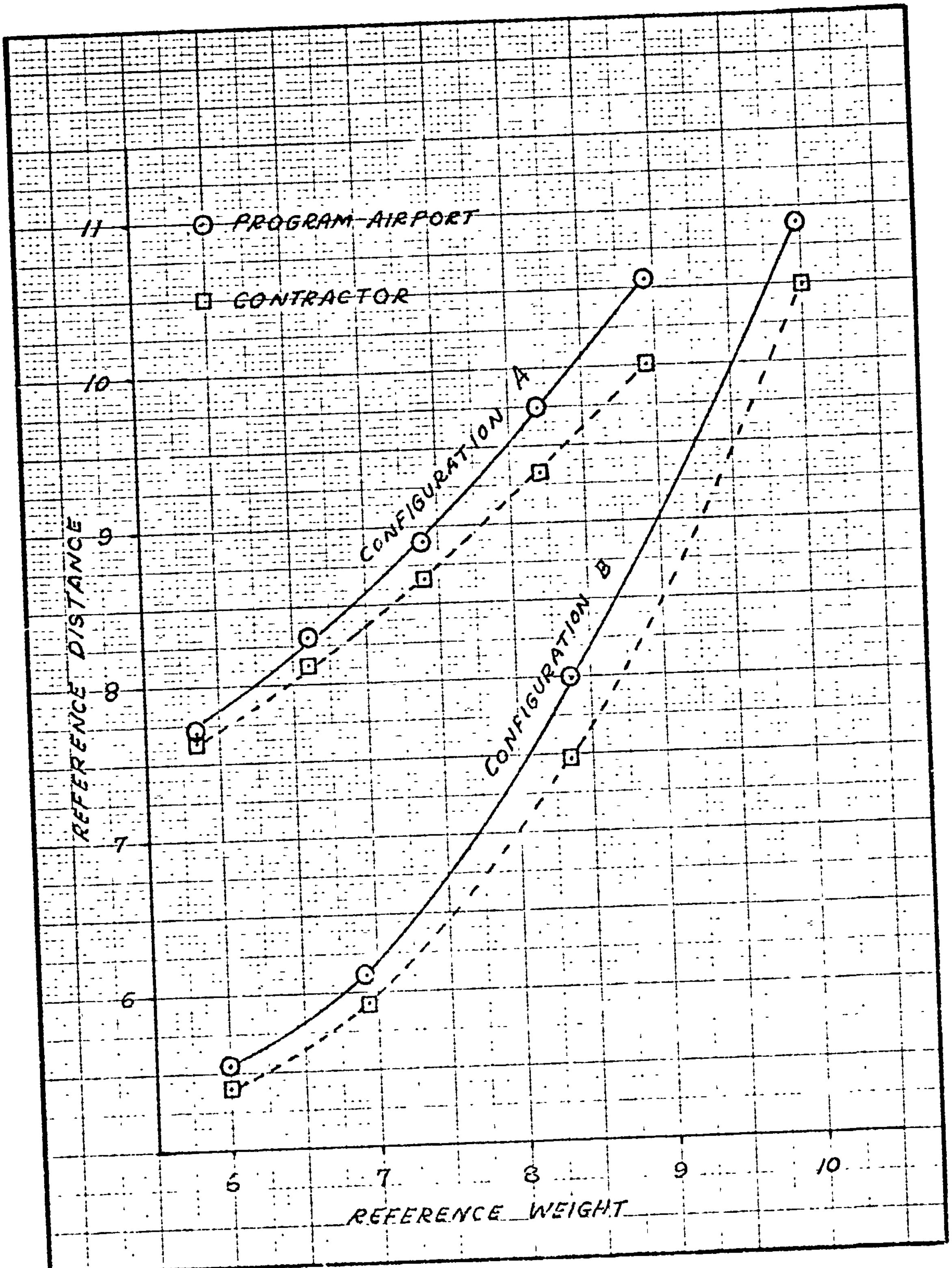

Figure 11. Landing Distance Comparison

IV. Conclusions and Recommendations

Conclusions

The analytical method provides a rapid means of accurately predicting the takeoff and landing characteristics for powered lift aircraft.

Program AIRPORT allows the takeoff and landing analyses to include a wide variety of parameters and thereby determine the sensitivity of the design to the operational conditions, design parameters and pilot reactions.

Recommendations

The presented technique is derived for the unique data characteristic of the powered lift aircraft. The digital program, however, is written in a modular form and can be easily modified. The method should be investigated for application to conventional aircraft. Also, since it has been evaluated for only the externally blown and upper surface blown flaps, other powered lift configurations should be evaluated.

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Appendix A

Computer Program User's Guide

This program was written to provide a rapid analytical means of estimating the takeoff and landing performance characteristics of powered lift aircraft. It is designed to operate using two separate programs, PREPORT and AIRPORT, where PREPORT serves as a preprocessor to create an input data file for AIRPORT. That is, PREPORT must be run prior to any AIRPORT runs.

Program PREPORT reads all the propulsion and aerodynamic data and prepares a mass storage file for use by program AIRPORT. Each data set is identified by a ten character alpha-numeric key word which is then used by AIRPORT to load the desired data. The propulsion data set for each key word consists of tables of gross thrust per engine and ram drag per engine as a function of Mach number for a single power setting. The aerodynamic data set for each key word consists of tables of lift coefficient and longitudinal force (drag) coefficient as a function of flap setting, angle of attack and thrust coefficient. Both the propulsion and aerodynamic data tables are read using linearly interpolating subroutines. An implicit assumption is made that the first aerodynamic data set will be in free air (out of ground effect). Since program AIRPORT requires both in ground effect and out of ground effect data, the in ground effect is defined in one of three methods: (1) reading a complete set of in ground effect data; (2) preparing a data set by analytically correcting the out of ground effect data using subroutine GROUND; or, (3) setting the in ground effect data equal to the out of ground effect data plus input constants for incremental lift and drag

coefficients. Subroutine GROUND is configuration dependent and, therefore, must be written, if used, for the specific aircraft being analyzed. After the aerodynamic data is read, the coefficients, CL, CD, and CJ are redefined into the inverse form: $CJ = \frac{1}{CJ}$, $CD = \frac{CD}{CJ}$, and $CL = \frac{CL}{CJ}$. The inverse coefficients are necessary because thrust coefficient is undefined when velocity equals zero. Dividing CL and CD by CJ results in nearly linear functions of $\frac{1}{CJ}$. The inverted coefficients are then stored on the mass storage file. The propulsion data may be printed out and the aerodynamic data may be either printed, plotted, or printed and plotted as output data.

Program AIRPORT is organized in three basic calculational phases: (1) all engines operating (AEO) takeoff distance to a specified obstacle height; (2) critical field length (CFL); and, (3) landing distance from a specified obstacle height. Each phase is independent of the others and, therefore, data required for a critical field length and landing distance need not be input if an all engines operating takeoff is all that is being estimated. In conjunction with the AEO takeoff and critical field length calculations, the aircraft climb gradient can also be computed as a function of velocity. Climb gradient with all engines operating is computed in conjunction with the AEO takeoff distance and the climb gradient with the critical engine inoperative is computed in conjunction with the CFL calculation.

Specifically, AIRPORT is a two-degree-of-freedom, point mass solution for the equations of motion. It consists of twenty-nine subroutines which perform the tasks of calculation, data handling and equation solving. The engine and aerodynamic data for the aircraft configuration is read from the mass storage file created by PREPORT by simply inputting the key words identifying each data set. The

remaining data is read by AIRPORT for the specific calculational types: (1) all engines operating takeoff; (2) critical field length; or, (3) landing distance. All of the data is read in a free field format; i.e., the data need not be placed in any specific column, however, each parameter must be separated by a comma.

The output data for program AIRPORT consists of input data, complete segment time histories and a summary of the segment distances. The input data and segment summaries are always printed while the time history print out can be suppressed. The velocities are output in knots, true airspeed, while all other units are presented in the lb-ft-sec system. The principal computational subroutines are briefly described as follows:

Subroutine AIRPORT is the main control program containing the logic for reading the input data, controlling the order of computation, and printing the output data.

Subroutine AEO computes the acceleration segment of the takeoff or critical field length where all engines are operating and the aircraft is at constant attitude. For an all engine takeoff, the final velocity is rotation speed. The aircraft configuration can change during this segment by extending the flaps at a specified velocity, VF. The final velocity for a critical field length is the critical engine failure velocity computed in subroutine BALANCE. In this case, the flap change, if applicable, is initiated at the engine failure velocity.

Subroutine ALPHADT computes the initial time required for the rotation phase by assuming a quadratic variation of the step time with velocity ($\Delta t = a + bV^2$) where the initial and final points at the rotation and lift-off velocities are known. This time estimate is used

to compute the initial roation rate which is then modified in an iterative procedure until the lift-off angle of attack and velocity are achieved simultaneously.

Subroutine ALPHALO computes the angle of attack for the given lift off conditions. Alpha liftoff is computed exactly at liftoff velocity while the distance computation uses an average velocity. Therefore, the lift force computed for the final step in the rotation segment will not be precisely equal to the aircraft gross weight.

Subroutine BALANCE computes the critical engine failure velocity using subroutine RTMI to find the zero of the balanced field function FCT(X) which is defined as $f(x) = D_{cont} + D_{rot} - D_{stop}$, where D_{cont} is the distance for the continued acceleration with the critical engine inoperative, D_{rot} is the rotation distance and D_{stop} is distance required to stop after the engine failed. The computation is limited to twenty passes in search of the solution for the critical engine failure velocity.

Subroutine BRAKE computes the stopping segment of the landing distance of critical field length. The initial stopping velocity is either touchdown velocity or critical engine failure velocity, as applicable. This subroutine includes the transition segment and contains the modeling of the configuration dynamics while the aircraft reconfigures to the full stopping conditions. The aircraft is allowed to continue accelerating during the initial part of the segment.

Subroutine CONT computes the distance for the aircraft to continue to accelerate from the critical engine failure velocity to rotation velocity with the critical engine inoperative. Angle of attack is constant and the failed engine is assumed to go instantaneously to zero thrust.

Subroutine FINDCD solves for the unique longitudinal force coefficient that corresponds to the computed value of lift coefficient and gross thrust coefficient for the desired climb gradient calculation. Subroutine SEARCH and function subroutine FCTCD are used to search the aerodynamic data tables and obtain the unique solution without explicit knowledge of the angle of attack.

Subroutine FINDCJ solves for the power setting and angle of attack required to fly the given landing approach flight path. These parameters are used to define the initial conditions for the landing ground roll.

Subroutine FORCE computes the summation of forces parallel and normal to the flight path for each integration step. The basic assumption is that the integration step size is small enough to consider the forces constant over the given integration step. First the forces are evaluated at the average velocity of each step and then the average acceleration, incremental time and distance are computed. Subroutine FORCE is used for all computational phases to compute the forces acting on the aircraft.

Subroutine LANDING computes the total landing distance from a specified obstacle height to a complete stop. The air distance computation assumes the velocity is constant and computes the distance based on the flight path angle at the obstacle, approach velocity, obstacle height, and the touchdown rate of sink. The power setting at touchdown is assumed to be equal to the thrust required to maintain the initial flight path angle. Angle of attack at touchdown is assumed to be equal to the approach pitch attitude. Landing ground roll includes a transition phase where the configuration dynamics are modeled linearly. Subroutines FINDCJ, FIND and SEARCH are used to compute the

thrust and longitudinal force for the given landing approach conditions.

Subroutine ROTATE computes the rotation segment of the takeoff distance and critical field length. During this segment the aircraft transitions from the taxi attitude at rotation velocity to the liftoff pitch attitude at liftoff velocity. The angle of attack is assumed to vary quadratically with time so the rotation rate is zero at each end condition. The solution is iterative in order to guarantee that the aircraft reaches its liftoff angle of attack at the same time it reaches lift off velocity.

Subroutine TAKEOFF computes the horizontal distance from liftoff to the specified obstacle height and velocity.

Subroutine VGAMACAL computes the steady state climb gradient as a function of velocity for the specified configuration. Ten velocity points are computed from the specified initial velocity and velocity increment.

The general subroutines used for data handling and equation solving are: CLOSMS, DECODE, NCHAR, INTERP, LOOKUP, OPENMS, READMS, TBL2, and TBL3.

A program listing, tape and operating instructions for programs PREPORT and AIRPORT may be obtained by contacting:

Mr. David F. LeMaster
ASD/ENFTA
Wright-Patterson AFB, Ohio 45433
Telephone: (513) 255-6834

VITA

David Powell LeMaster was born on 1 October 1942 in Huntington, West Virginia. He graduated from high school in Huntington in 1960 and attended Marshall University from which he received the degree of Bachelor of Engineering Science in May 1964. Upon graduation, he was employed by the United States Air Force at Wright-Patterson Air Force Base, Ohio as an Aerospace Engineer. In June 1972, he entered the School of Engineering, Air Force Institute of Technology.

Permanent Address: 3123 Westview Drive
Xenia, Ohio 45385

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A numerical technique based on known methods was developed to predict the takeoff and landing performance characteristics of powered lift aircraft. Two-degree-of-freedom equations of motion treating the aircraft as a point mass are integrated using numerical techniques based on Euler's method of forward integration. The analysis includes the calculation of all engines operating takeoff distance, critical field length, landing distance and climb capability. Predictions were made for aircraft with externally blown

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flaps and upper surface blown flaps and compared with the performance quoted by the respective airframe manufacturer. Good correlation was achieved.